# RESEARCH ACTIVITIES AT THE INSTITUTE OF ELECTROTECHNOLOGY IN THE FIELD OF METALLURGICAL MELTING PROCESSES

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*Annotation* — **A wide range of industrial metallurgical melting processes are carried out using electrothermal and electromagnetic technologies. The application of electrotechnologies offers many advantages from technological, ecological and economical point of view. Although the technology level of the electromagnetic melting installations and processes used in the industry today is very high, there are still potentials for improvement and optimization. In this paper recent applications and future development trends for efficient use of electromagnetic processing technologies in metallurgical melting processes are described along selected examples which are part of the research activities of the Institute of Electrotechnology of the Leibniz University of Hannover.**

***Keywords: metallurgical processes, induction melting, electromagnetic levitation, electromagnetic processing.***

## INTRODUCTION

Electrotechnologies are an indispensable part of many industrial processes in particular in the production and further treatment of products in metallurgical applications. In many cases the processing and in particular heating and melting of materials can, in principle, be realized by using electrical energy or fossil energy sources. However, due to the continually growing demands on the effectiveness of the whole process chain, on the level of flexibility and automation, on the environmental sustainability of industrial processes, on the reliable quality and not at least on the improvement of the total energy and CO2-emission balance of a process or a product, electrical energy used in processing technologies in many cases offer excellent future oriented application possibilities in many industrial processes [1].

The major advantages of electrotechnologies in particular induction processing technologies can be shortly described as follows:

- heat can be generated within the workpiece,
- high energy density and consequently fast heating,
- demanded temperature distributions within the workpiece,
- high temperature, if required,
- flexible operation and low thermal inertia,
- selective, localized heating, if required,
- clean heating in any media including vacuum or controlled atmosphere,
- high reliability,
- electro dynamic forces on liquid electrically conducting material for stirring, braking, homogenizing, confining or separating of inclusions.

The application of induction processing technologies allows a desired processing which is easily reproducible and means that defined material properties can be set in order to improve the technical characteristics of the semi finished or final product. Using electric or in particular induction heating the fast heating-up rate, the exact temperature control and the predictable spatial temperature distribution result in high thermal efficiency and noticeable saving of raw material, e.g. due to the low combustion losses.

Although the applied electrotechnologies stand for a high level of development, there are nevertheless rooms for improvement and optimization. In the following, various approaches, recent applications and future development trends in the efficient use of electromagnetic processing of metal and non-metallic materials are described along selected examples, which are part of the recent research activities at the Institute of Electrotechnology of the Leibniz University of Hannover in the field of metallurgical melting processes.

## MELTING IN INDUCTION FURNACES

The research activities for melting applications in induction furnaces like induction crucible or induction channel furnaces are concentrated on the computer simulation and experimental investigation of the turbulent melt flow in particular the heat and mass transfer in the melt flow of the metallurgical processes.

At the Institute of Electrotechnology new numerical calculation methods have been developed in the last years, which allow the simulation of in-stationary three-dimensional turbulent melt flows. The new simulation tools allow to investigate the mass and heat transfer in induction furnaces in order to analyze and to optimize the flow behaviour concerning low local overheating of the melt, less wear of the lining due to reduced overheating, reduced build-up effects specially in the field of light metals, sufficient melt mixing for temperature and melt analysis homogeneity and optimal alloying.

Industrial metallurgical processes like melting of alloys in induction furnaces has become a subject of numerical modelling since many years. A wide range of different modelling approaches for the simulation of the turbulent melt flow and the heat and mass transfer processes have been developed. But up to now the question about an universal and always reliable modelling approach, which can be used for the development and design of industrial metallurgical applications, remains open.

*Induction crucible furnace*

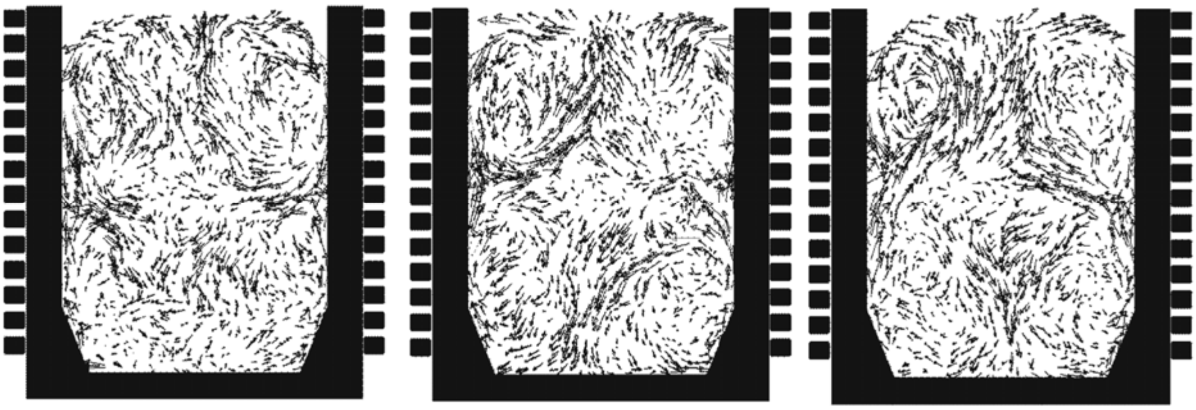
Melting of alloys in induction crucible furnaces can be mentioned as a wide spread example of numerical modelling, because this process can be approximated with two-dimensional (2D) axial-symmetric model. The flow pattern in these installations is formed by the influence of electromagnetic forces and usually comprises of two or more toroidal dominating recirculating vortices. Flow patterns obtained with two-dimensional solvers based on Reynolds Averaged Navier-Stokes (RANS) equations usually are in good agreement with estimated and measured time-averaged flow velocity values. The resulting spatial distribution of the temperature and alloys compound concentration depends strongly on the heat and mass exchange between vortices of mean flow. Numerical investigations show that two-dimensional turbulence models, e.g. k-ε and others, fail to describe correctly the heat and mass transfer processes between the main vortices.

At the present time, different modelling techniques are being used to achieve better agreement with the experiment. Our own engineering approach developed for this problem is described in [2], however, it is necessary to investigate advanced simulation methods for more generic and therefore universal flexible solutions. Due to the permanent growth of accessible high powerful computational resources, nowadays, it is possible to run more complicated transient and three-dimensional (3D) numerical calculations of fluid dynamic problems using advanced turbulent models with higher time and volume resolution requirements and to get reliable results in reasonable time.

Concluding all these preconditions the calculations presented in this paper are devoted to the application of Large Eddy Simulation (LES) method for turbulent recirculating flows. The flows of this character often occur in various industrial processes where liquid metal is driven by electromagnetic forces.

The simulation of the turbulent melt flow in an industrial crucible furnace is presented here as the first example of our LES numerical investigations. This furnace has a melt volume of about 0.9 $m^3$ at 100% filling level. The radius of the crucible furnace is about 0.49 m and the height of the inductor is 1.34 m. The furnace is used for melting grey cast iron, which has a density of 6,800 $kg/m^3$. The three-dimensional hydrodynamic model consisted of about $7 \cdot 10^5$ elements and the time step in the transient calculations was $10^{-2}$ s. Industrial crucible furnace differs from the experimental installation with higher EM forces density and noticeable free surface deformation (meniscus).

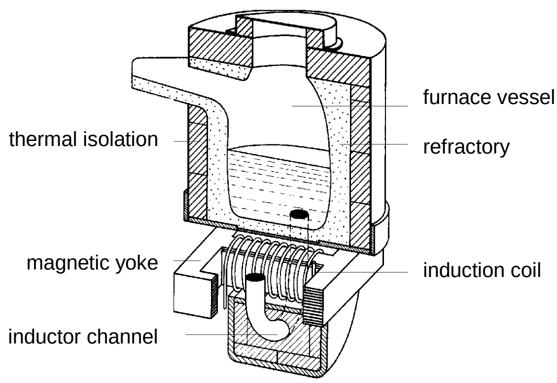
The comparative analysis of LES and experimental data from model furnace allows applying this numerical method also for industrial scale installations, and qualitatively similar phenomena is achieved. The period of the low-frequency oscillations become smaller – 2 seconds – because of significant increase of the rotational velocity of the flow eddies. Initially axial symmetrical flow pattern becomes fully three-dimensional, but the symmetry remains in the time-averaging of the fluctuating flow (Picture 1).



Pic. 1. Velocity distribution [m/s] in an industrial induction crucible furnace calculated three dimensional in-stationary with Large Eddy Simulation (LES) after 20 (left), 21 (centre) and 22 seconds

*Induction channel furnace*

The second example presented here is devoted to the induction channel furnace (ICF), which is used for holding and casting of ferrous and non-ferrous metals and due to its good efficiency for melting of non-ferrous metals. Picture 2 shows the principle design of a one loop ICF, which is typically used for holding and casting of grey cast iron.



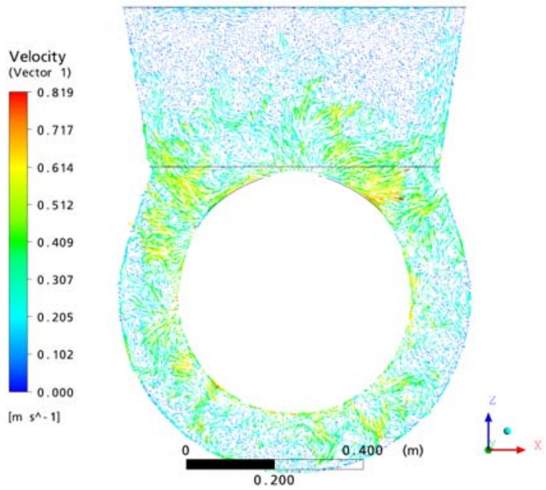

Pic. 2. Principle design of an one loop induction channel furnace

The ICF basically consist of a ceramic lined furnace vessel and one or several inductors. In principle, the inductor can be regarded as a transformer with iron yoke, where the induction coil is the primary circuit and the melt filled inductor channel represents the secondary short-circuited loop. For the safety and efficient operation of the ICF the heat transport from the channel, where the Joule heat is generated, to the melt bath in the furnace vessel is important in order to avoid a local overheating in the channel.

The induction channel furnace is well established for melting, holding and casting of metals. But up to now there are still open questions and room for improvements regarding the heat and mass exchange in the inductor channel itself and between the channel and the melt bath and in particular regarding the operation life time of the inductor, which is strongly limited by wear and tear damages like erosion, clogging and infiltration of the ceramic lining in the inductor channel.

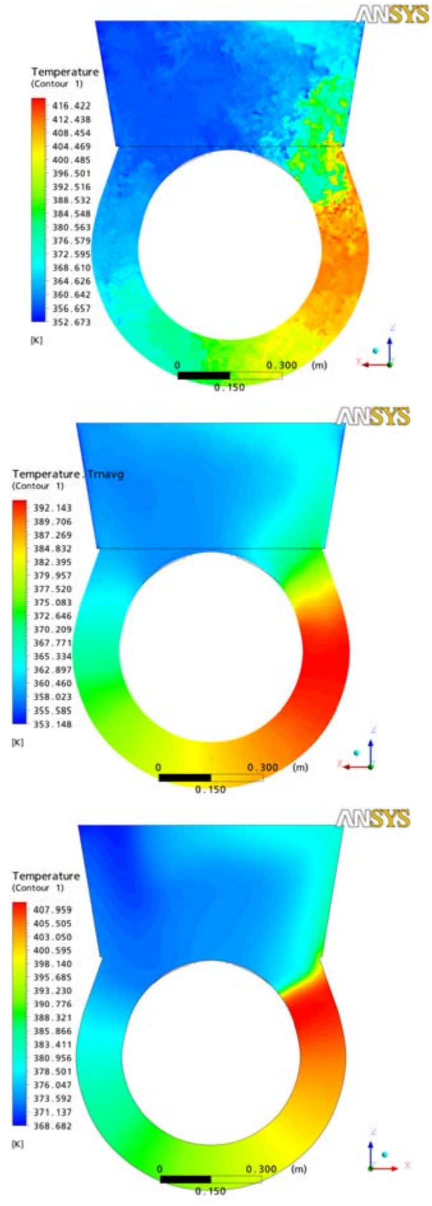
The melt flow in the channel itself and in the transition zone between the channel and the bath, the so-called inductor-throat, is very complex, highly turbulent and influenced mainly by electromagnetic forces but additionally by buoyancy forces. In order to investigate the operation behaviour of the ICF heat and mass transfer processes in the melt have been analysed applying the Large Eddy Simulation (LES) approach. The simulation results are verified by already existing data of melt flow velocity and temperature measurements.

The simulation results presented here are carried out for an industrial sized experimental furnace running with Wood metal as a model melt. The results are obtained using the two parameter or LES model show highly turbulent 3D dynamic flow vortex structures, with flow velocities up to 70 cm/s. The steady state velocity distribution in the symmetry plane calculated with the k-ε model shows, that the flow is directed radial outwards in the channel and there is up-flow just above the channel forming two vortex loops in the bath. These loops have complex structure and are closed on front wall of the bath. Instantaneous velocity pattern calculated with the LES model. Picture 3 shows highly turbulent structure of the flow. However even here the regions of more or less symmetric structures and constant direction flow can be observed.




Pic. 3. High turbulent structure of the melt flow in the induction channel furnace calculated with LES model

Results of the simulation of the temperature distribution in the symmetry plane of the channel furnace are shown in Picture 4. The initial state with the channel maximal temperature in the bottom point is unstable and small velocity fluctuations can shift it to the left hand or right hand side on the channel, where it becomes stable corresponding to the transit convectional flow. Our investigations have shown, that the position of the magnetic yoke, which leads to unsymmetrical electromagnetic field and *Joule* heat distribution in the channel, influences the shift of the temperature maximum to the left hand or right hand side. Due to the dynamic interaction of the turbulent vortexes the heat and mass exchange along the channel is well developed. The dynamic flow structure in the throat of the channel inductor leads to a smooth temperature gradient in the transition zone between the channel and the bath, which is shown as a result of the LES model. But the results of the steady state temperature distribution, calculated with the k-ε model (Picture 4 down) show a precipitous temperature gradient at the exit of channel, because the interactions between the flow vortexes in this region, which are characterized by low frequency oscillations, are not taken into account according to the real situation with the two parameter turbulence models.



Pic. 4. Temperature distribution in the channel furnace. Up: intermediate distribution after 45 sec (LES), middle: time averaged over 60 sec (LES), down: steady-state (k-ε model)

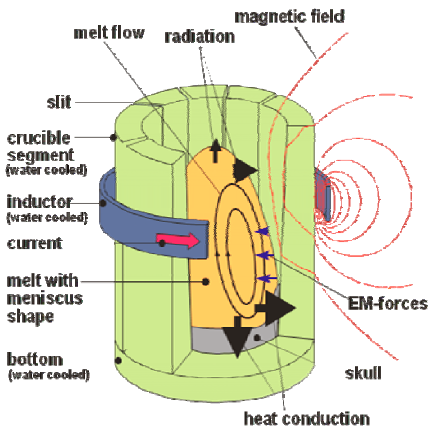
Performed long-term computations have shown transient characteristics of turbulent heat and mass exchange in industrial induction channel furnaces in wide range of flow time [3].

The distribution of alloying additions injected into the melt or impurities infiltrated into the melt due to erosion of channel ceramic lining has been investigated. The distributions of inert particle clouds are obtained along with LES modelled distributions of turbulent velocity and thermal fields.

Different newly designed channel geometries have been analyzed numerically in order to find an optimized shape of the channel, which leads to reduced build up formation at channel walls in the transition zone to the bath.

*Cold crucible induction furnace*

Melting of high-purity cast products is often carried out in the induction furnace with cold crucible (IFCC), which offers various technological and economical advantages, like high-purity cast products as well as melting, alloying and casting in one process-step.




Pic. 5. Schematic view of an induction furnace with cold crucible (IFCC)

This furnace consists of copper crucible made of base part and split wall segments which are isolated from each other in order to allow the alternating electromagnetic field, which is initiated by the inductor wound around the crucible, to couple with the charge material. The eddy currents induced in the charge generate Joule heat for melting the metallic material. Both the crucible segments and the base plate are intensively water-cooled in order to prevent the crucible itself of being melted. As result, the charge material which is in contact with the construction parts, remains in the solid state and efficiently isolates the melt from the contamination. With typical operating frequency of about 10 kHz the most of the molten mass is being pushed from the walls by the electromagnetic field (semi-levitated), therefore preventing the excessive heat losses and providing high overheating temperature. Also, the intensive stirring driven by the Lorentz forces assures good chemical homogenisation of the melted alloys. Melting process can take place in normal or controlled atmosphere as well as in vacuum. The process itself can be periodical with separate pouring (trough the nozzle or by tapping the whole crucible) into the forms, or uninterrupted, when bottom of the crucible continuously descends with solidified material and new charge material is being loaded from the top.

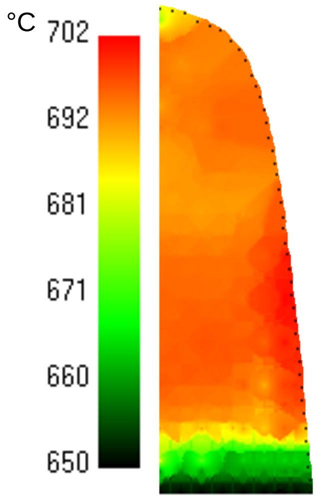
The typical electrical efficiency of the installation, i.e. part of the energy which is induced in the charge material, is about 30%, when the rest of the energy is lost in the inductor (~15%) and wall segments. The electric currents induced in the wall segments not only lead to the increased energy losses, but also influence the electromagnetic field pattern, which becomes non-axis-symmetric. Therefore, the modelling of melting process in the cold crucible requires three-dimensional approach. The task of optimizing melt overheating faces the challenge of finding optimal combination of crucible height to diameter ratio, number of inductor turns and crucible sections, current strength and frequency. Changing of any mentioned factor influences the shape of melt meniscus and, as a result, flow pattern and energy balance. Therefore, solving of this problem should be based on determination of main tendencies for given direction of parameter change. This could be done performing numerical calculations for series of process configurations, with only one of parameters being varied.

The main distinguishing feature is that the melt is kept in the water-cooled crucible and, therefore, high-purity of material is assured by solid skull layer at the melt-crucible contact zone. Practical experiences show that the overheating temperature of the entire melt, which is determined by the electromagnetic, hydrodynamic and thermal process factors, is one of the key parameters of this technological process.

In order to optimize the maximization of the overheating temperature the induced power in the melt should be as high as possible and the heat losses via radiation and in particular the heat conduction losses to the crucible bottom and crucible wall should as small as possible. Therefore the shape of free surface is very important because the electromagnetic coupling between the melt and the inductor should maximal and the heat losses by conduction to the crucible bottom and wall should be minimized. But it is nearly impossible to realize such shape of the free surface.

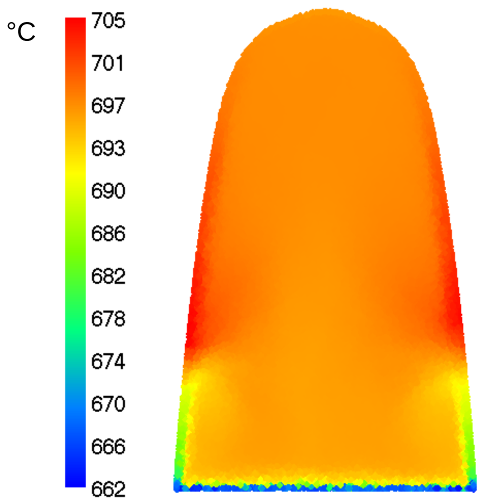
Experimental investigations are necessary in order to evaluate numerical simulation models. They are performed using pure aluminium (99.5%) as a model melt. In the Institute of Electrotechnology a cold crucible with a radius of 7.8 cm and a height of 26 cm is used, where 6 kg of aluminium are melted during the experiments. The output power of the generator is up to 300 kW at a frequency range 8-10 kHz. The meniscus height reached up to ~22.5 cm when a power of 200 kW is applied. With these process parameters the meniscus shape of the melt surface is quite stable and therefore it is possible to perform detailed investigations of the free melt surface itself, the temperature field and the turbulent melt flow.

The temperature distribution was measured using NiCr-Ni thermocouples, which were placed in a protective ceramic tube to avoid their destruction in the very aggressive aluminium environment during long-lasting experiment. However, due to this protection, the thermal inertia of the thermocouple was quite long (~2.8 s), therefore, it was possible to measure only time-averaged temperature values. The time-averaged temperature field as it was measured is shown in the Figure above on the left hand side. The lowest temperatures are at the water-cooled bottom, where was detected the solid skull layer with thickness about 10 mm. Also the radiation losses from the free surface lead to the formation of relatively cold area at the top. And the highest temperatures are observed in the intensive inductive heating region. The temperature distribution in the rest of the melt is more or less homogeneous.




Pic. 6. Measured temperature distribution in the aluminum melt of an induction furnace with cold crucible

The resulting time-average velocity field looks very similar to the one predicted with 2D steady-state calculations, as well as quite good agrees with experimental observations. However, 3D transient approach allows to model accurately the heat transfer processes in such flows, where two or more recirculated eddies are interacting [4]. The calculated flow pattern at the each time-step is not symmetrical, and simulation shows, that the flow is intensively oscillating. Those oscillations provide convective heat transfer mechanism, which is possible to simulate numerically only using transient three-dimensional calculation techniques. The time-averaged temperature distribution calculated with LES is more homogeneous, than in case of 2D modelling and resembles the measured temperature field. In the pictures series with temperature field at the consequent time-steps it can be observed how relatively cold melt masses from below penetrate into upper vortex area and are dissolved there.




Pic. 7. Time averaged temperature distribution in the IFCC with aluminum melt calculated with the LES model

The 3-dimensional numerical investigations of TiAl melting process produced similar results in terms of flow pattern, although the meniscus height in this case is lower due to the increased density of the material. The flow velocities are slightly higher (average velocity at $r = 0$ is about 55 cm/s), therefore the temperature distribution is more homogeneous, than in aluminium. Due to the noticeably higher R/H ratio of the melt shape, the low-velocity zone exists in the middle of the bottom region, which may lead to the thicker skull layer above the water-cooled base. Therefore, the modification of the crucible's geometry or load is considered as a possible way to improve the efficiency of the process.

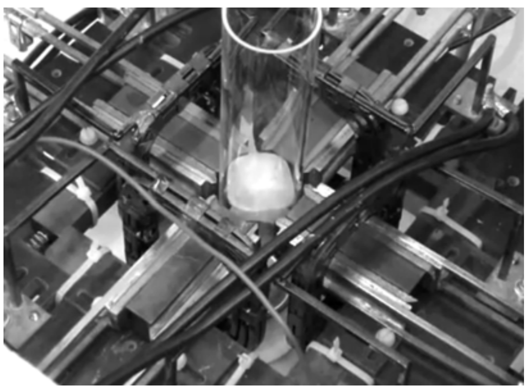
*Electromagnetic levitation melting*

In conventional axisymmetric melting furnaces with electromagnetic (EM) levitation, the Lorentz force vanishes on the symmetry axis. The melt outflow and leakage can be hindered in this lowest point on the axis of a levitated sample only by the melt surface tension and therefore, the charge weight is limited.

The new method developed at the Institute of Electrotechnology applies two homogeneous EM fields of different AC frequencies, whose field lines in the absence of a charge are horizontal and reciprocally normal in order to exert EM lift forces also on the axis of the levitated sample,. Therefore the weight of the charge can be increased and the charge can be drip- and leakage-free melted. The method can be used in a melting furnace, as well as for the coreless induction valves applied for flow rate control, e.g. in the continuous casting of molten metals.

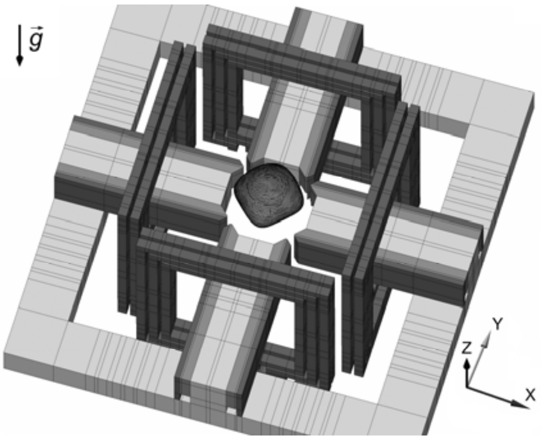
In parallel a numerical model for simulation and optimization of particular EM levitation melting technology has been developed. EM induced turbulent flow and free surface dynamics computation is ensured by means of coupling between 3D electromagnetic calculation in *ANSYS* and 3D two-phase hydrodynamic calculation in *FLUENT* and *CFX* [5].

The modified setup consists of two separate pairs of water-cooled coaxial inductor coils with orthogonal axis orientation that generate horizontal and perpendicular EM fields (Picture 8). In order to obtain greater magnetic induction in the region of levitating droplet the EM field is conducted by the yoke ends and effectively looped in the outer yoke. The quartz tube is placed between yoke ends in order to prevent unexpected contact between molten metal and furnace parts.



Pic. 8. Experimental installation of EM levitation melting setup with two orthogonal horizontal EM fields

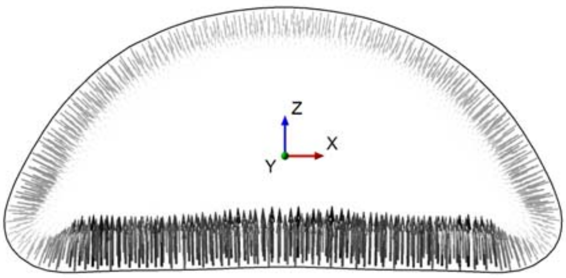
The corresponding numerical simulation model of the EM levitation melting setup is shown in Picture 9.



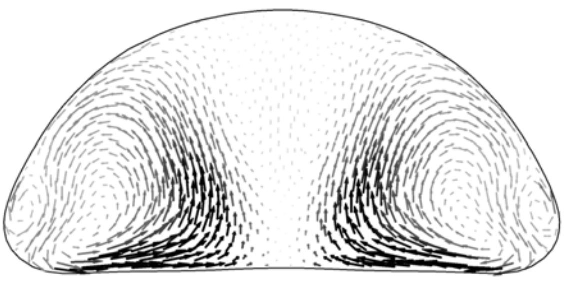

Pic. 9. 3D simulation model of EM levitation melting setup with two orthogonal horizontal EM fields

In order to levitate greater charge volume EM fields of two different quasi non-interacting frequencies f1 = 21.6 kHz and f2 = 29.0 kHz must be applied for the case of experimental setup presented in Figure 8.

Our 3D numerical calculation results for the Lorentz force density distribution (Picture 10) and steady regime flow pattern (Picture 11) on orthogonal cross-sections illustrate the quasi steady state of molten aluminum levitation in two-frequency (f1 = 21.6 kHz and f2 = 29.0 kHz) EM levitation melting setup.

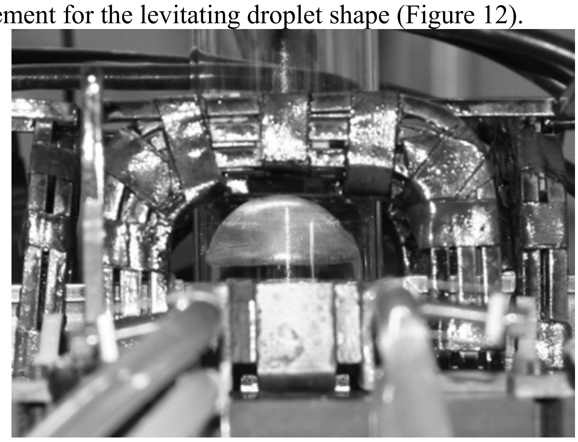


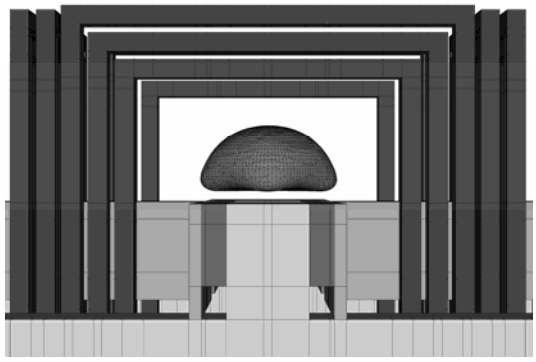

Pic. 10. Simulation results of the 3D Lorentz force density distribution of the EM levitation melting setup with two orthogonal horizontal EM fields



Pic. 11. Simulation results of the quasi steady state flow pattern of the EM levitation melting setup with two orthogonal horizontal EM fields

The qualitative comparison between experiment photo and picture of numerical model also reveals a good agreement for the levitating droplet shape (Figure 12).





Pic. 12. Qualitative comparison between experimentally observed numerically simulated EM levitation in two-frequency orthogonal and horizontal EM field

The proposed method for drip- and leakage-free EM levitation melting of metallic samples with greater weights and axisymmetrically stabilized positions has been successfully validated both numerically and experimentally. Using the developed numerical approach it is planned to tailor the design of setup, as well as configuration of EM field, in order to meet the conditions for stable EM levitation of industrial-scale molten metal charge and reproduce it in the laboratory experiment.

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